The Effect of an Isogrid on Cryogenic Propellant Behavior and Thermal Stratification

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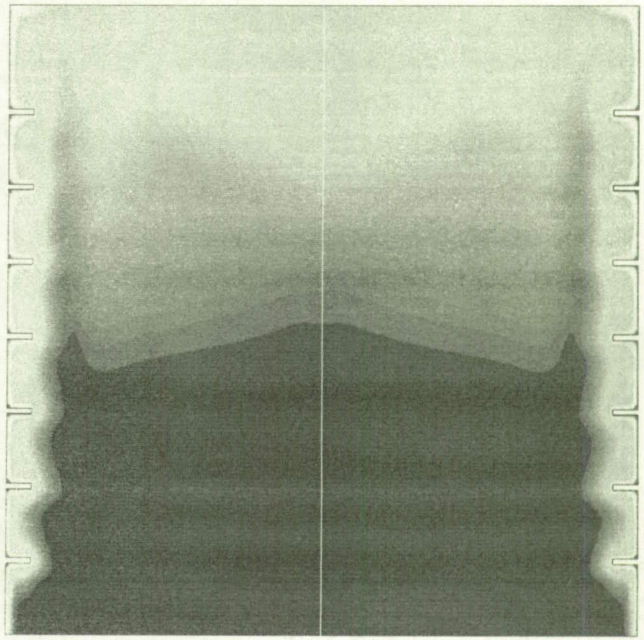
CONTENTS

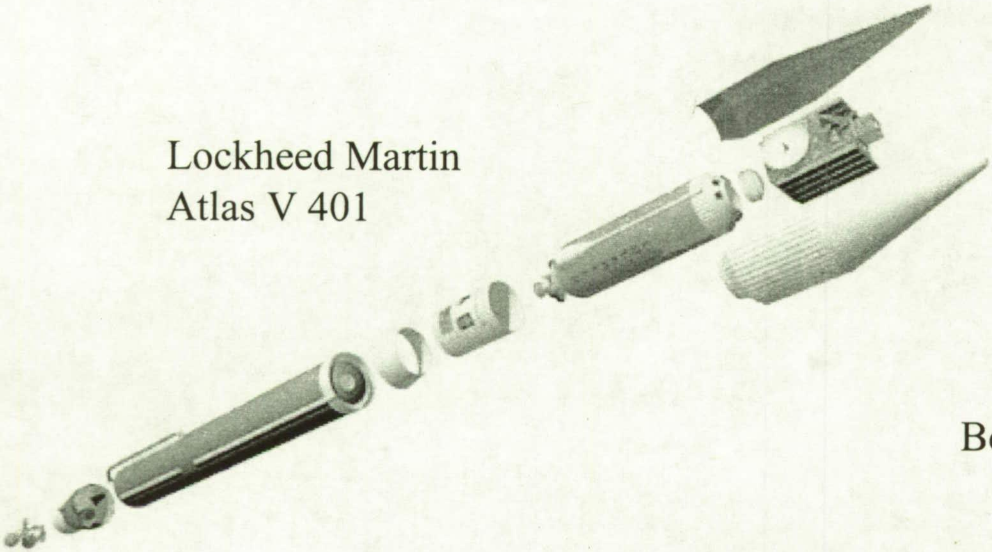
- **Overview**
- Computational Modeling
- Current Work
- Future Work
- Concluding Remarks

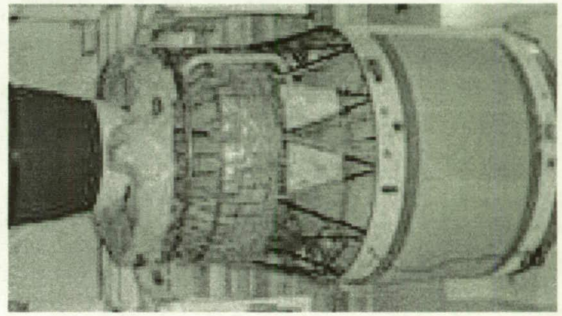


OVERVIEW

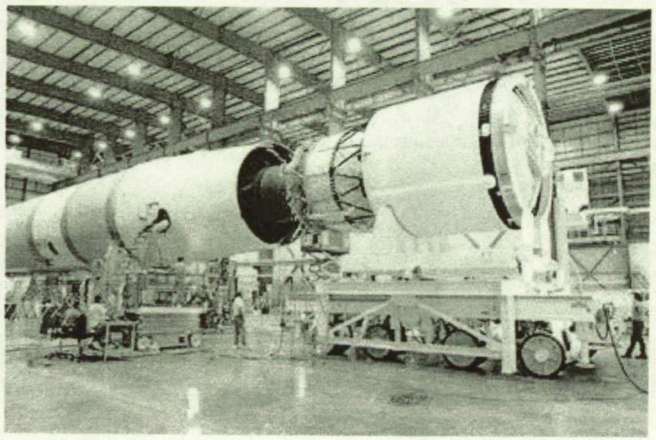
UPPER STAGE MODELING

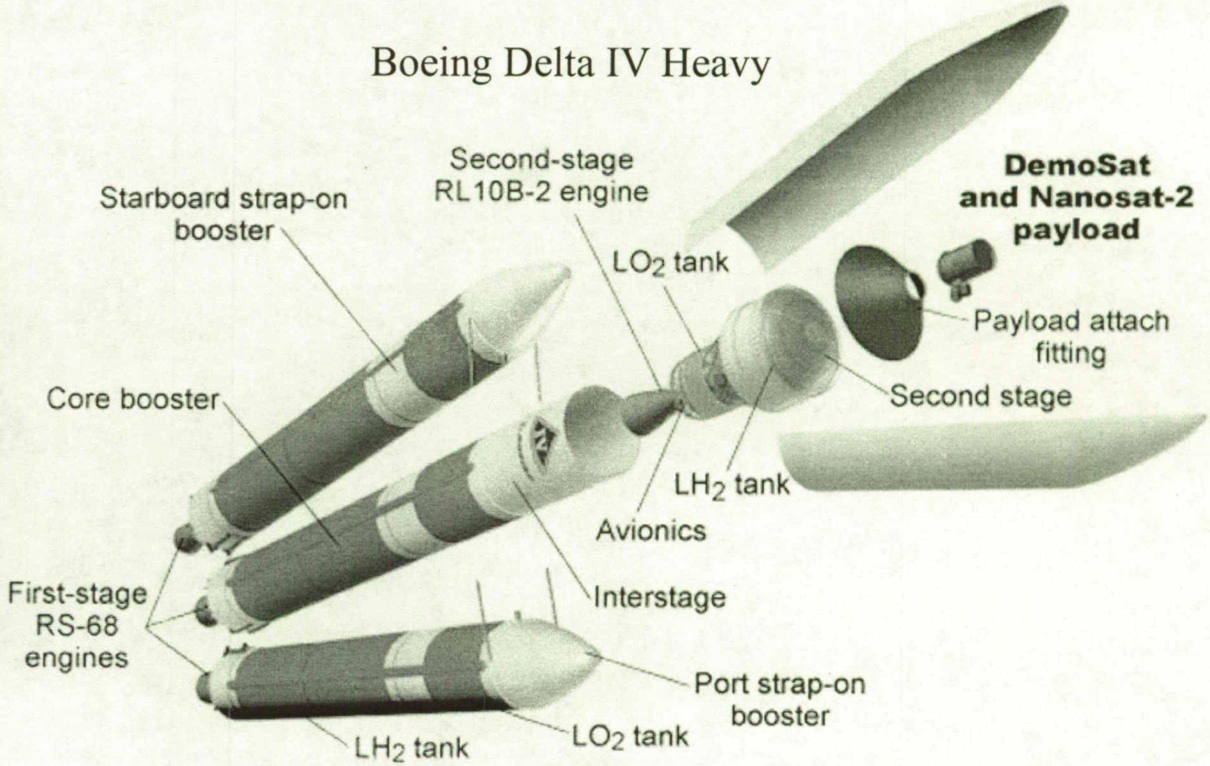
Lockheed Martin
Atlas V 401





Boeing Delta IV Heavy

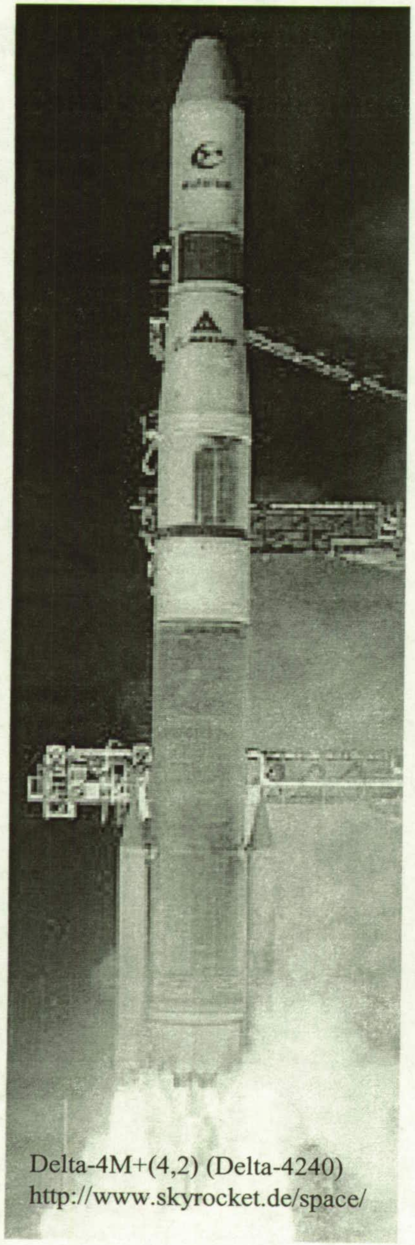




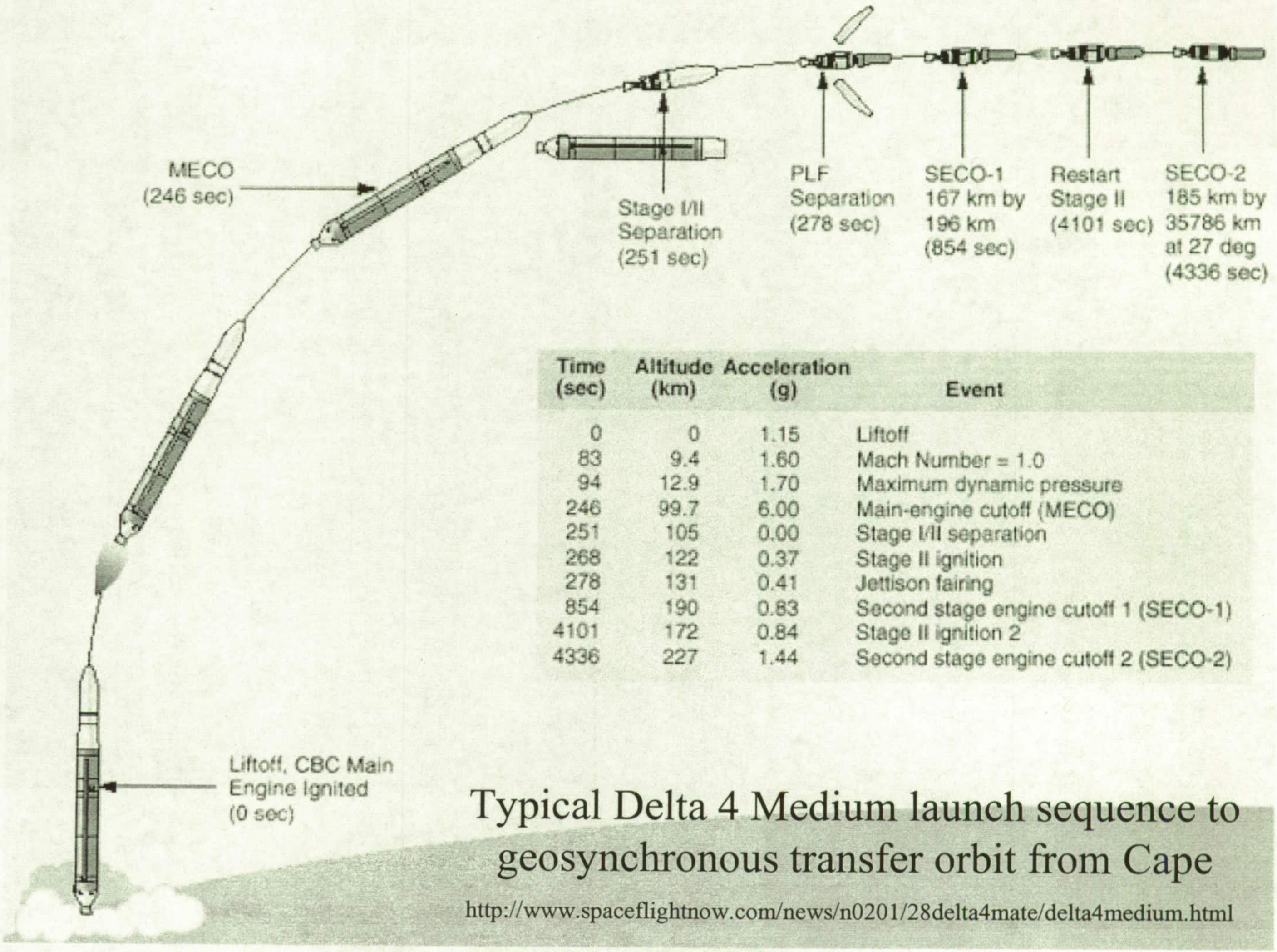
http://www.boeing.com/defense-space/space/delta/delta4/d4h_demo/book04.html

MOTIVATION

- During LEO → GEO transfer, upper stage coasts for several hours
- Upper stage must re-start at conclusion of coast phase for insertion



Delta-4M+(4,2) (Delta-4240)
http://www.skyrocket.de/space/

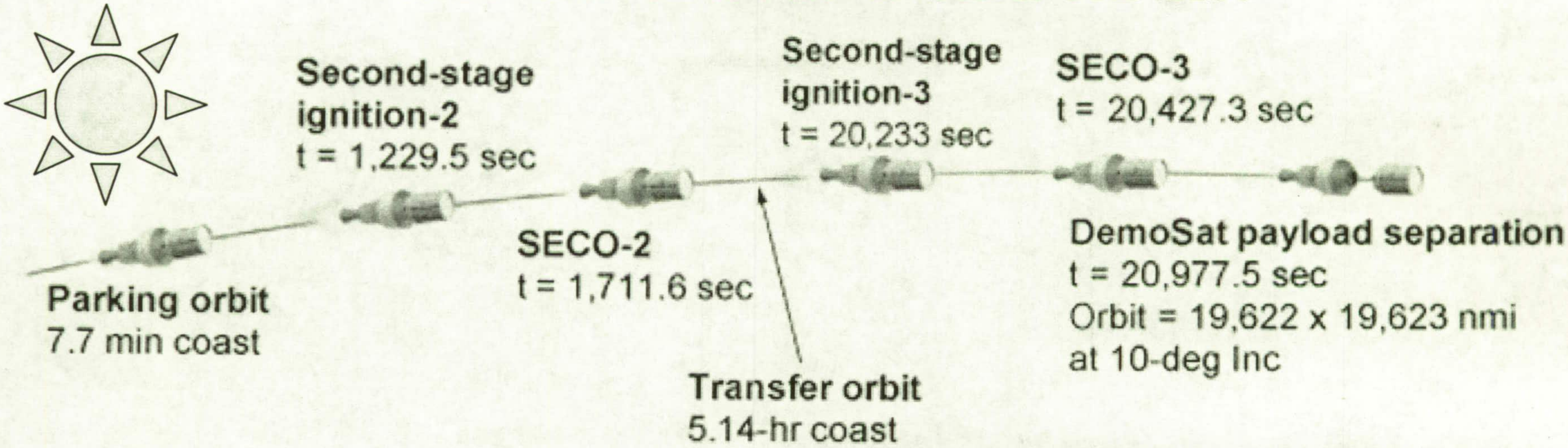


Time (sec)	Altitude (km)	Acceleration (g)	Event
0	0	1.15	Liftoff
83	9.4	1.60	Mach Number = 1.0
94	12.9	1.70	Maximum dynamic pressure
246	99.7	6.00	Main-engine cutoff (MECO)
251	105	0.00	Stage I/II separation
268	122	0.37	Stage II ignition
278	131	0.41	Jettison fairing
854	190	0.83	Second stage engine cutoff 1 (SECO-1)
4101	172	0.84	Stage II ignition 2
4336	227	1.44	Second stage engine cutoff 2 (SECO-2)

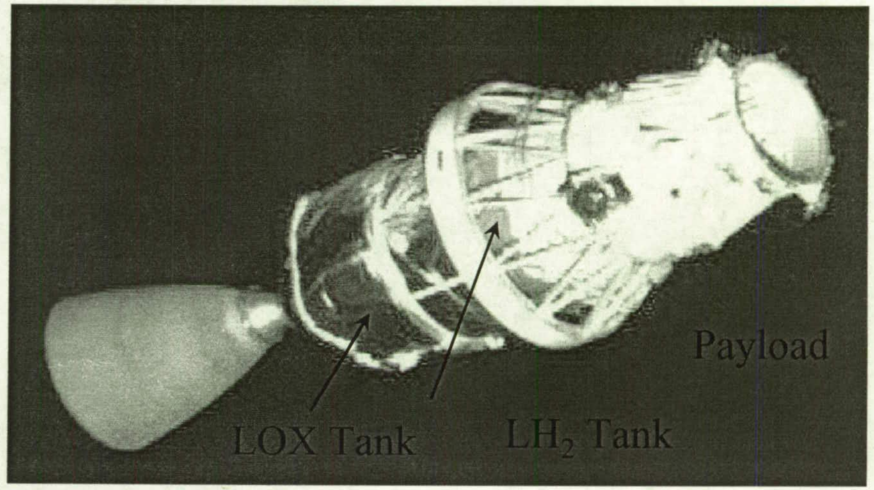
Typical Delta 4 Medium launch sequence to geosynchronous transfer orbit from Cape

http://www.spaceflightnow.com/news/n0201/28delta4mate/delta4medium.html

WHAT CAN HAPPEN INSIDE TANKS?



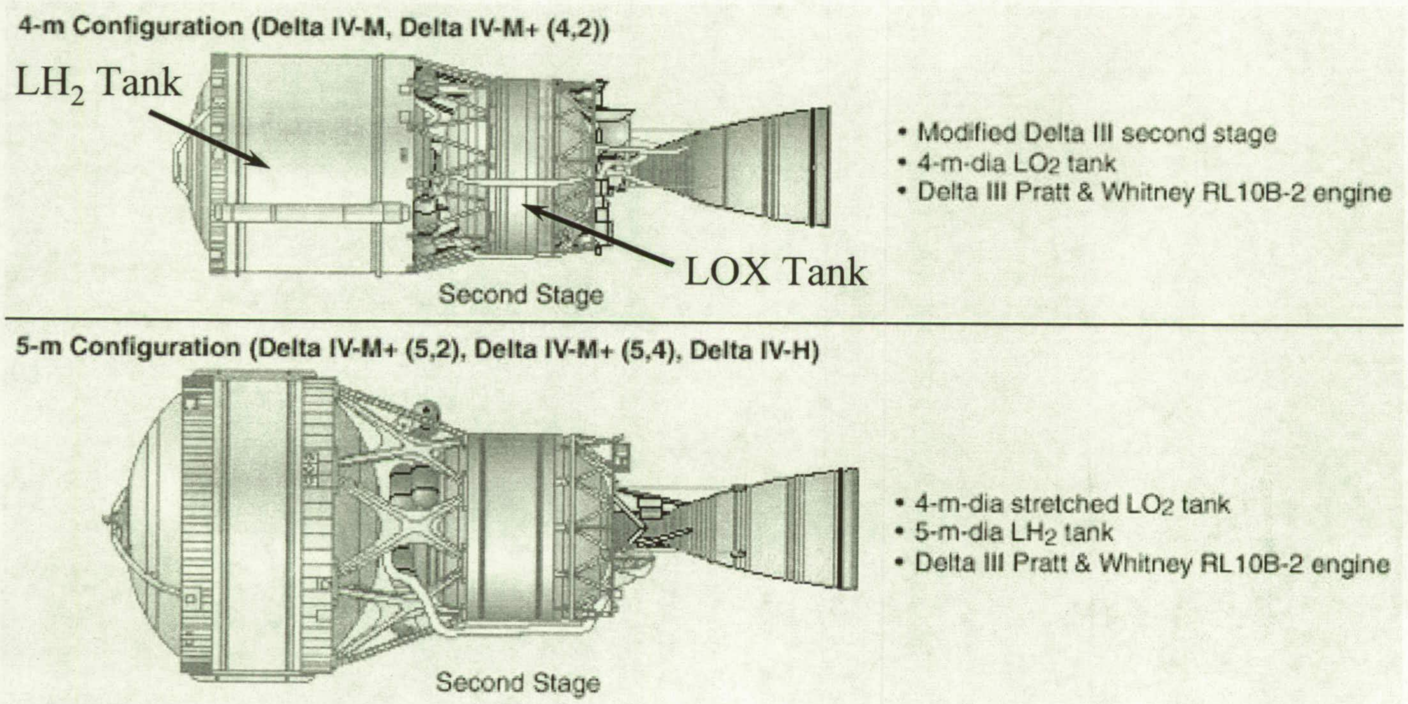
- Stage exposed to solar heating
- Propellants (LH_2 and LOX) may thermally stratify
- Propellants may boil
- Slosh events during maneuvers



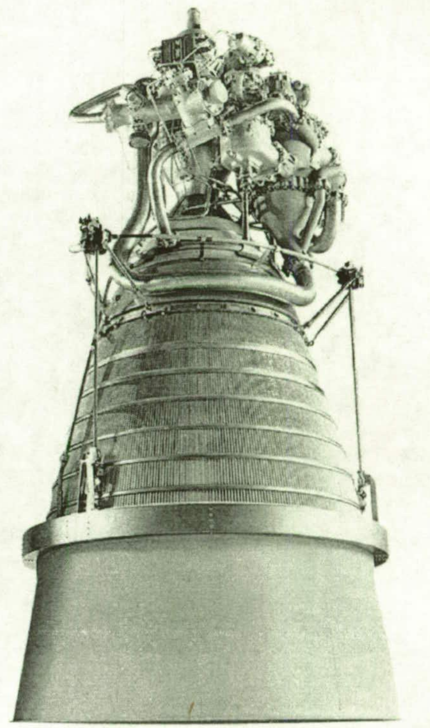
http://www.boeing.com/defense-space/space/delta/delta4/d4h_demo/book14.html
XSS-10 view of Delta II rocket: An Air Force Research Laboratory XSS-10 micro-satellite uses its onboard camera system to view the second stage of the Boeing Delta II rocket during mission operations Jan. 30. (Photo courtesy of Boeing.), http://www.globalsecurity.org/space/systems/xss.htm

WHY IS IT IMPORTANT?

- Propellant T&P must be within specified range for turbomachinery operation
  - If propellants outside specified T&P box engine may not restart
  - Orbit cannot be circularized

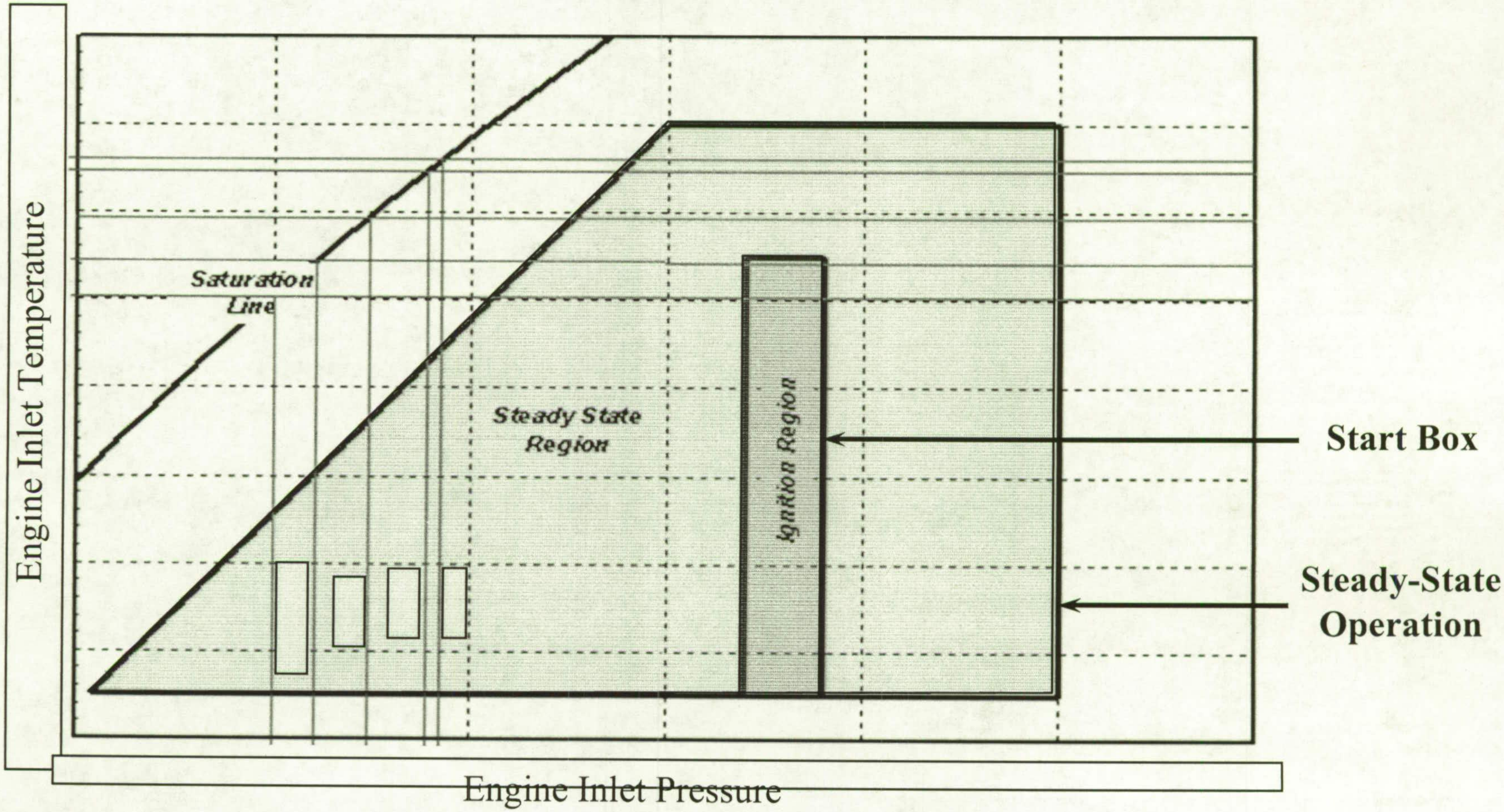


http://www.spaceflightnow.com/news/n0201/28delta4mate/delta4upperstage.html



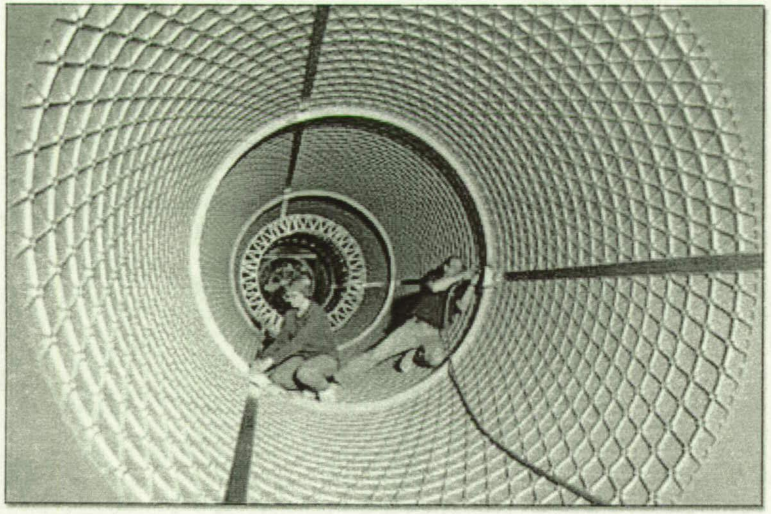
http://www.pratt-whitney.com/prod_space_rl10.asp

ENGINE START AND OPERATIONAL REQUIREMENTS



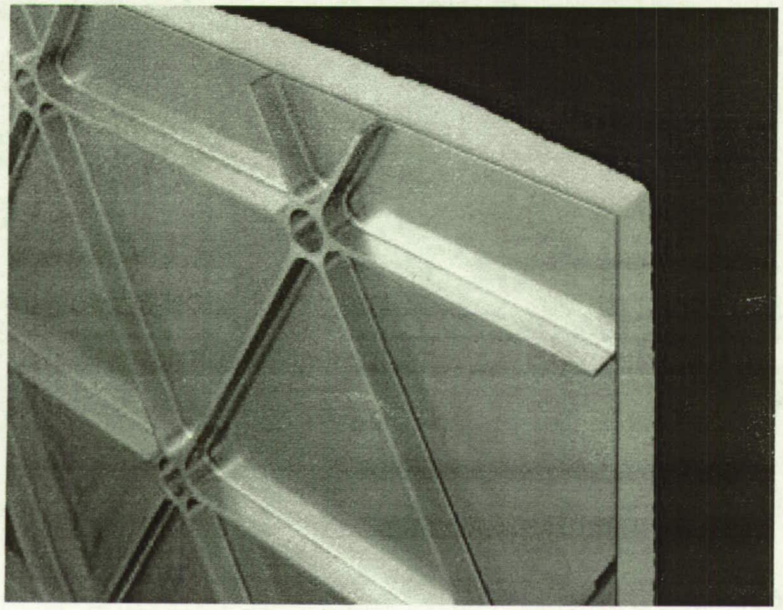
- Propellants must be within a narrowly defined range of temperature and pressure to guarantee engine ignition (restart) at conclusion of coast phase
- Generic LOX map shown

WHAT HAPPENS WITH ISOGRID WALLS?

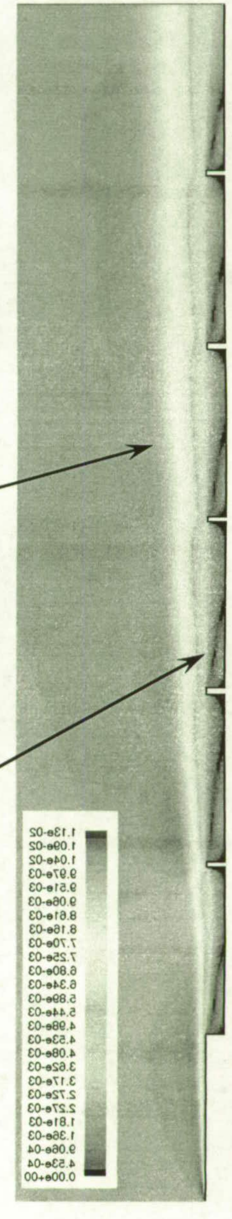


MIKE McCORMICK PHOTO

Technicians Pat Garlen (left) and Chris Batie drill splice plates for the intermediate frames on a Delta II rocket liquid oxygen tank in Decatur, Ala.



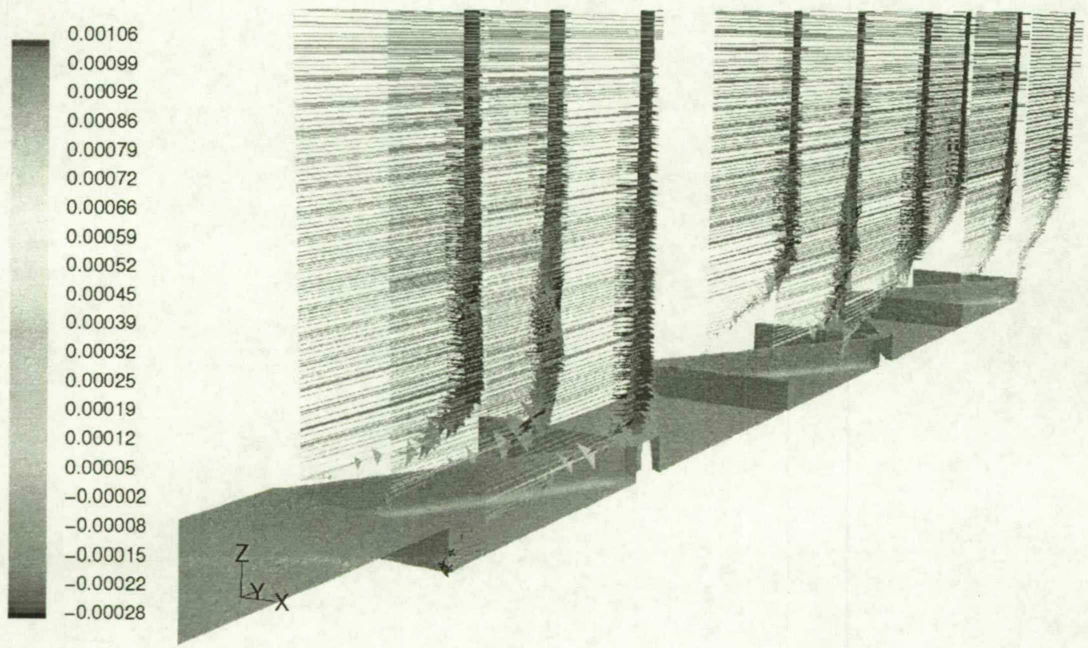
- Boundary layer profile important for mass flow (thickness of stratum) and heat transfer (temperature of stratum)
- In LH_2 tank isogrid wall is present
- Is this momentum and thermal boundary layer similar to laminar, turbulent or something different?
- What is influence of recirculation zones?
- Pursuing numerical and experimental work to assess boundary layer profile with full Gr and Re matching



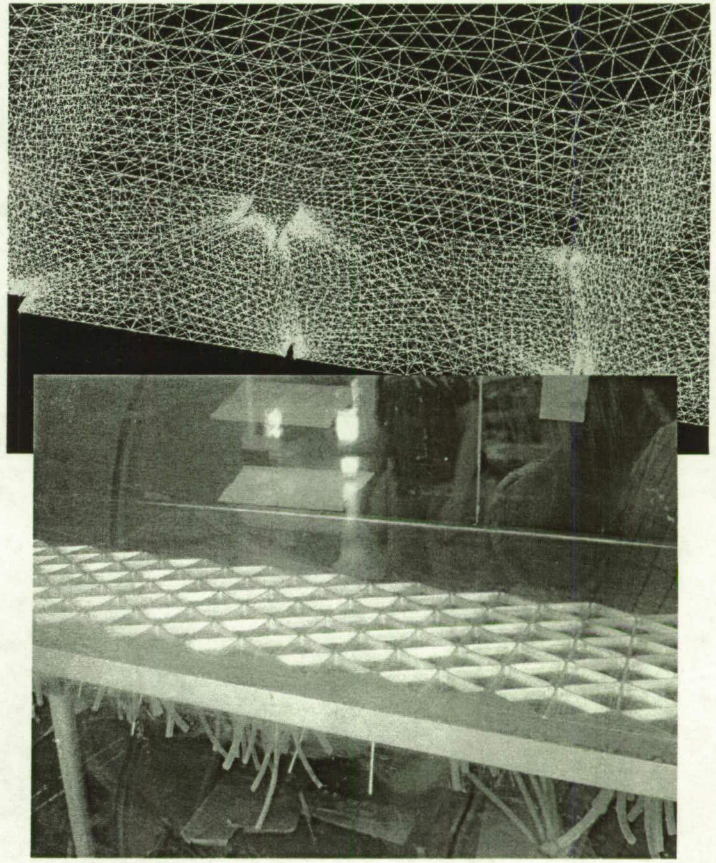
COMPUTATIONAL MODELING

Computational Modeling: Introduction

- Forced flow CFD analysis over Isogrid performed
  - compared with flat plate analysis
  - boundary layer thickness compared to flat plate
- Results show Isogrid with 200-450% larger boundary layer compared to flat plate
- Good agreement in trends with windtunnel experiment



Velocity Vectors Colored By Y Velocity (m/s)



Computational Modeling: Introduction

- Forced flow CFD analysis give qualitative result to boundary layer thickness of Isogrid surface
- Free convective CFD models needed to properly asses stratification
- Framework first developed for smooth wall tanks; compared to theory

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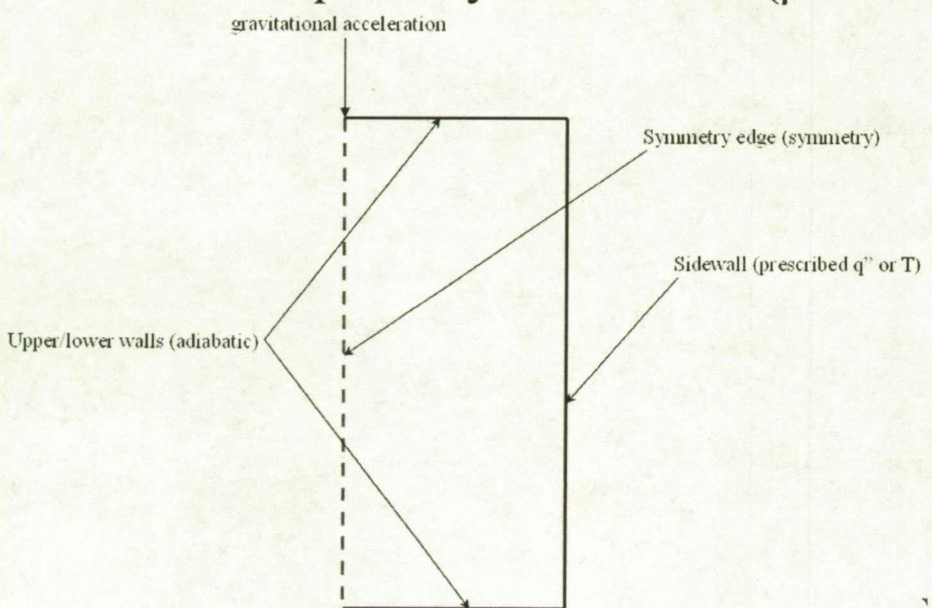
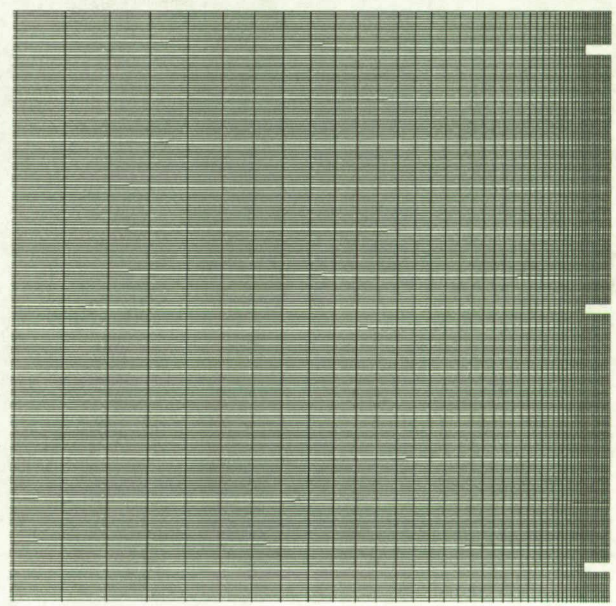
- Computational modeling done in FLUENT
- Free convective CFD model developed using
  - Unsteady coupled implicit solver
  - Boussinesq density model used (ρ const. except in buoyancy term in mom. eq.)





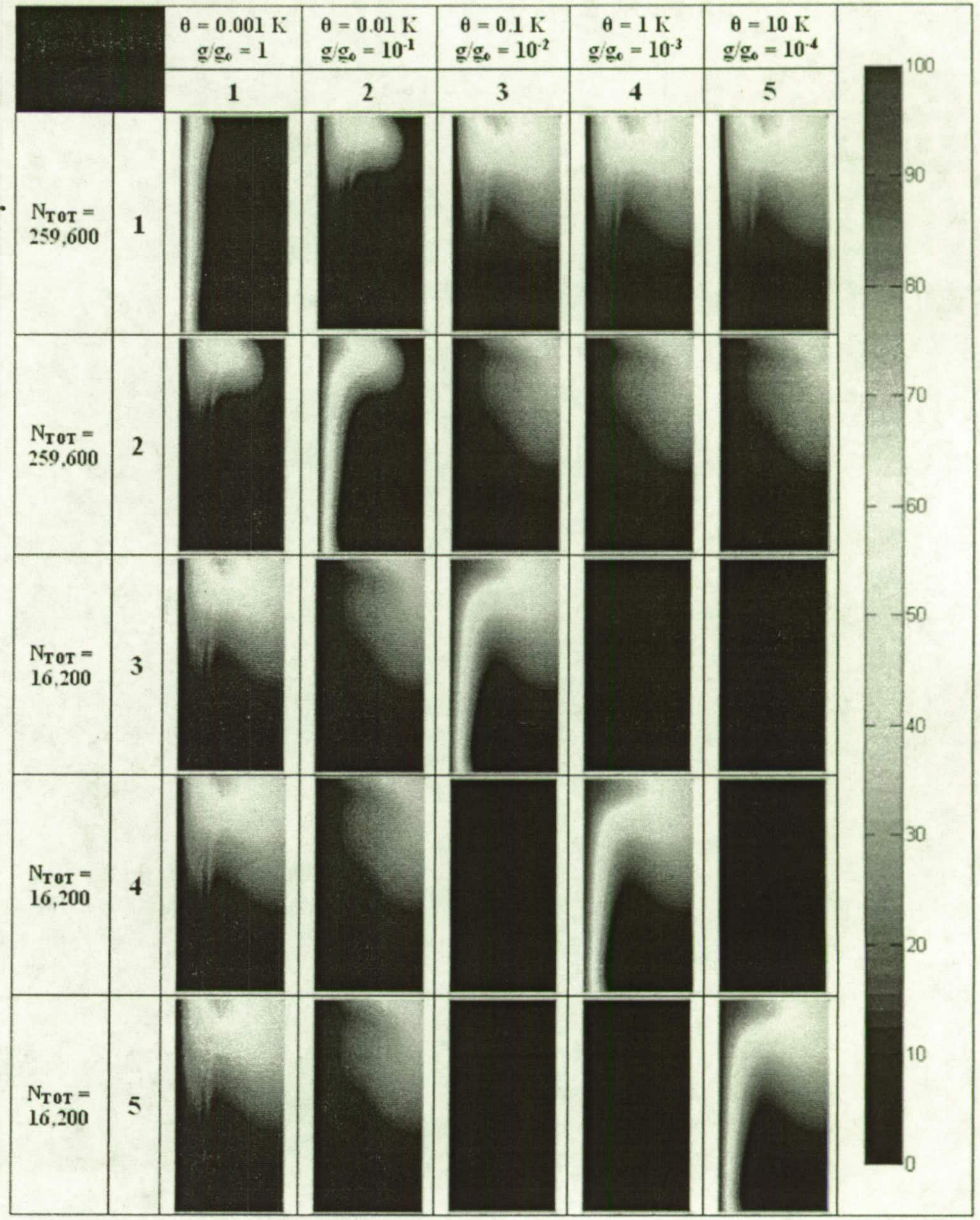
Computational Modeling: Smooth wall

- Simulations run to check Ra scaling on smooth wall tanks
- Temperature contours compared after 10,000 seconds using non-dimensional temperature,

$$\xi = \left(\frac{T - T_\infty}{T_{wall} - T_\infty} \right) \times 100\% = \left(\frac{\theta_{\{x,y\}}}{\theta_{wall}} \right) \times 100\%$$

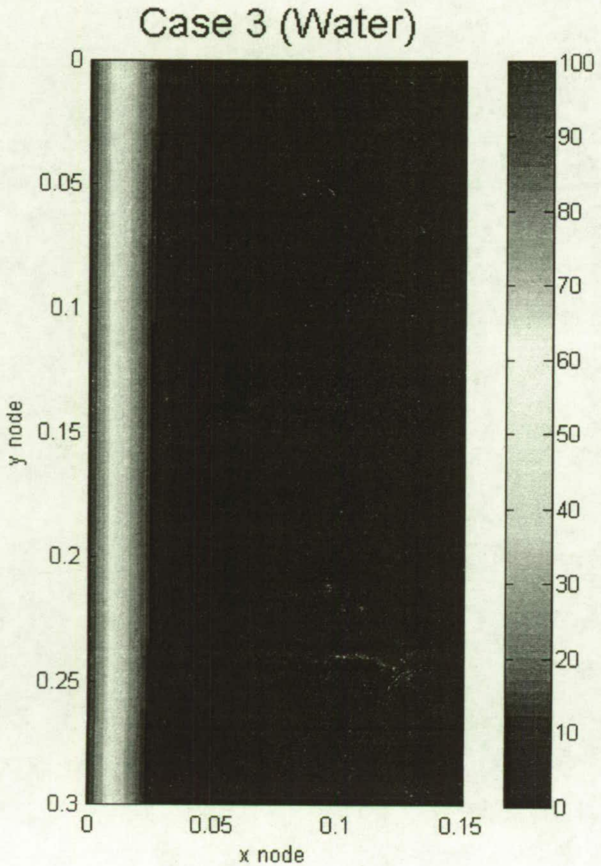
- Map interpreted as:

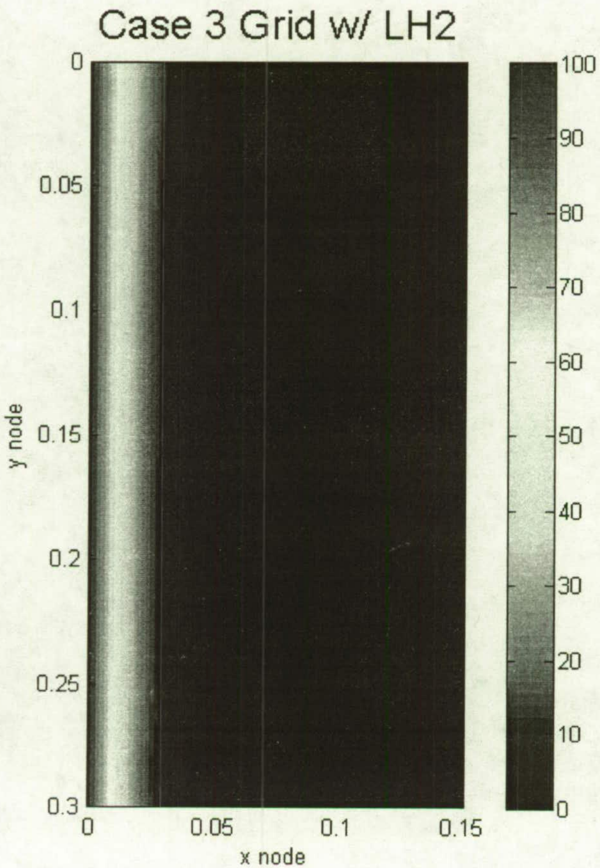
  the results from [col. #] mapped onto the grid of [row #]

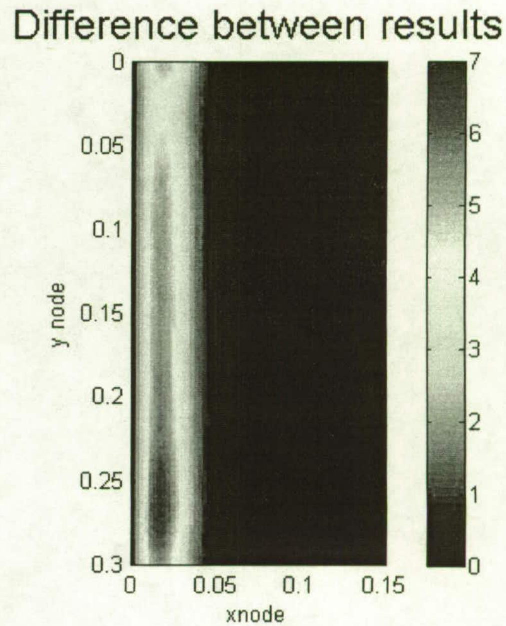


Computational Modeling: Smooth wall

- Ra scaling held extremely well at gravity levels below 10^{-1}
- Ra scaling also checked between fluids (Water and LH2)
  - < 7 % difference in results after 1 hour

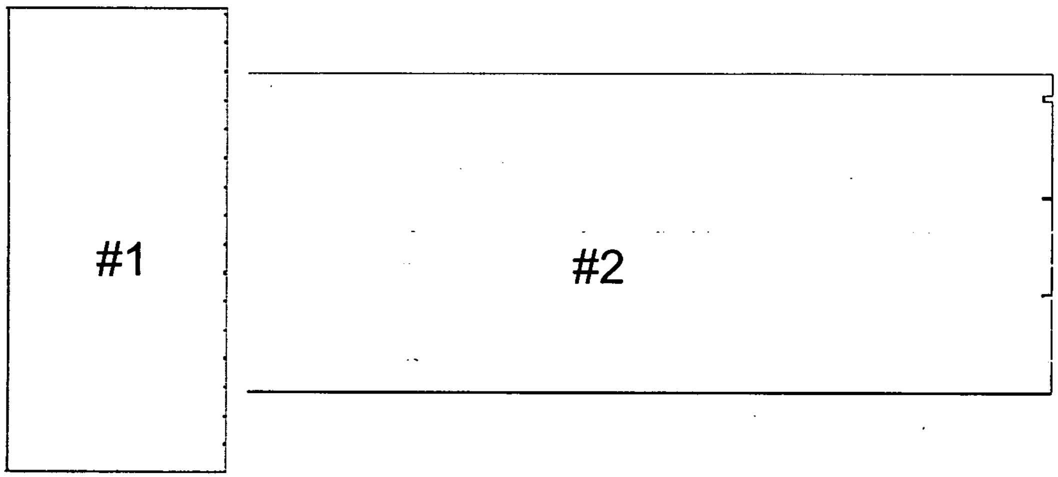






Computational Modeling: Rough walls

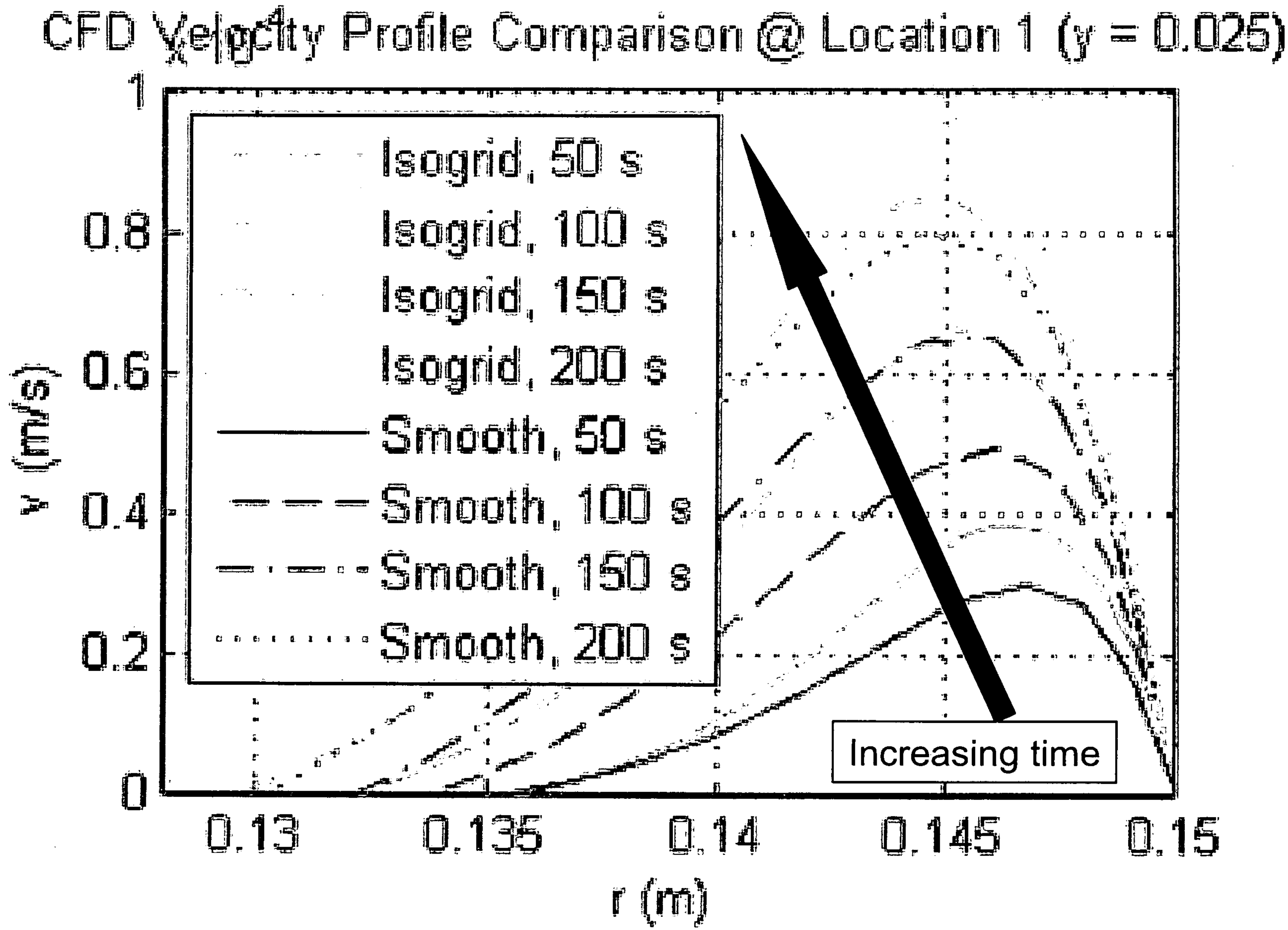
- 2 roughness configurations
  1. 1/10 scale Isogrid baseline case
  2. Full-scale tank at 20% fill level



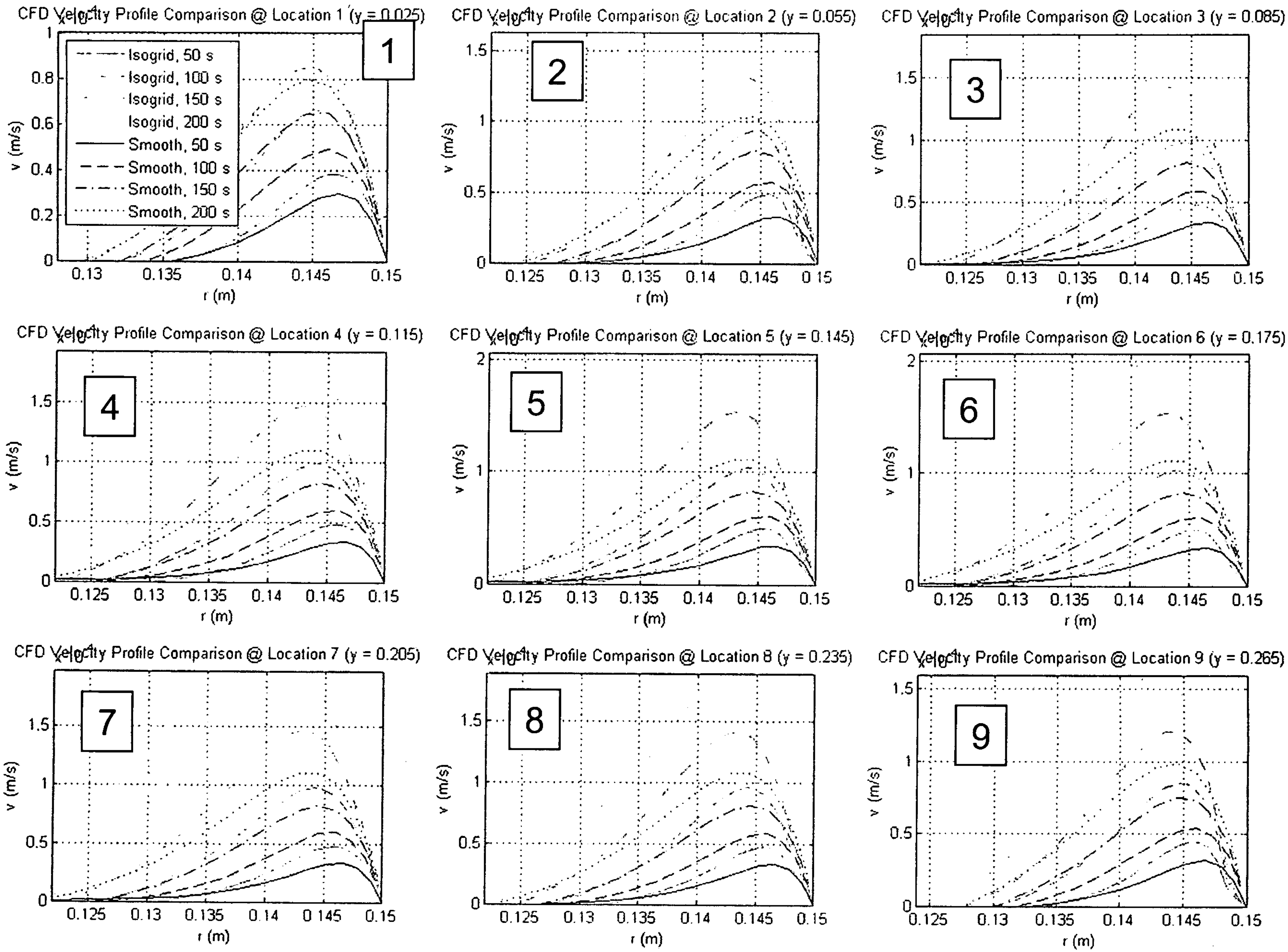
- Velocity and temperature sampled at 9 vertical tank locations

Location 9	y = 0.265 m
Location 8	y = 0.235 m
Location 7	y = 0.205 m
Location 6	y = 0.175 m
Location 5	y = 0.145 m
Location 4	y = 0.115 m
Location 3	y = 0.085 m
Location 2	y = 0.055 m
Location 1	y = 0.025 m

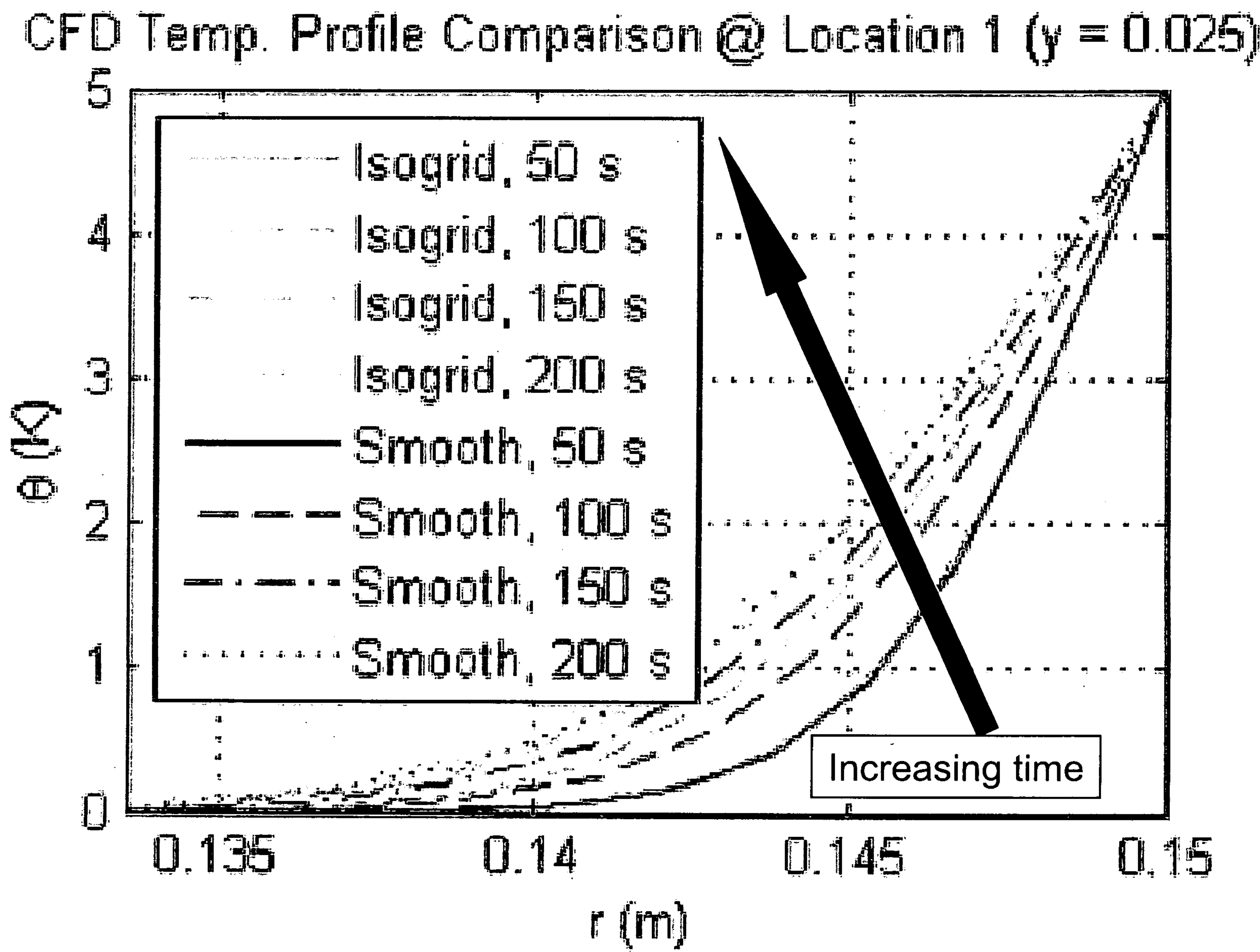
EXAMPLE OF VELOCITY PROFILES AT LOCATION 1 JUST ABOVE 1st ISOGRID ELEMENT



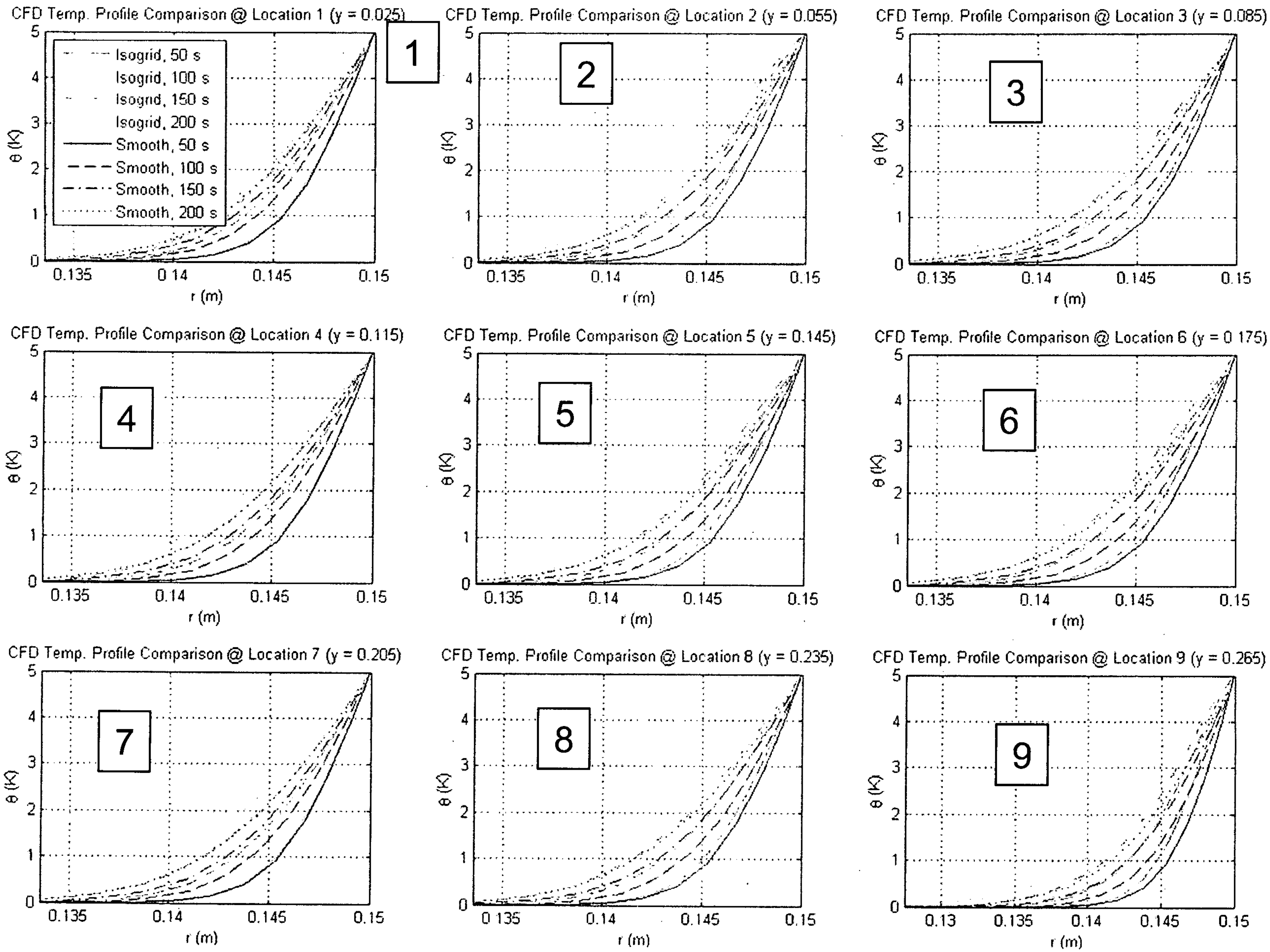
VELOCITY PROFILES AT LOCATIONS 1-9



TEMPERATURE PROFILES AT LOCATIONS 1-9

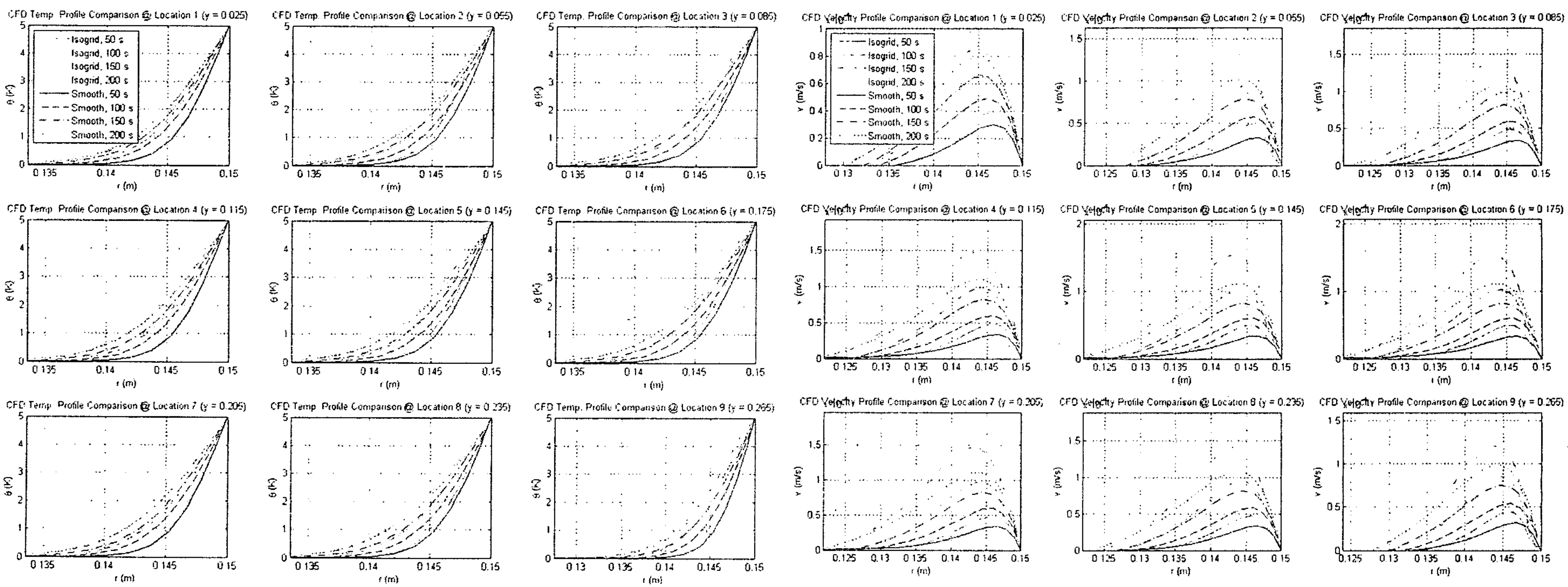


TEMPERATURE PROFILES AT LOCATIONS 1-9



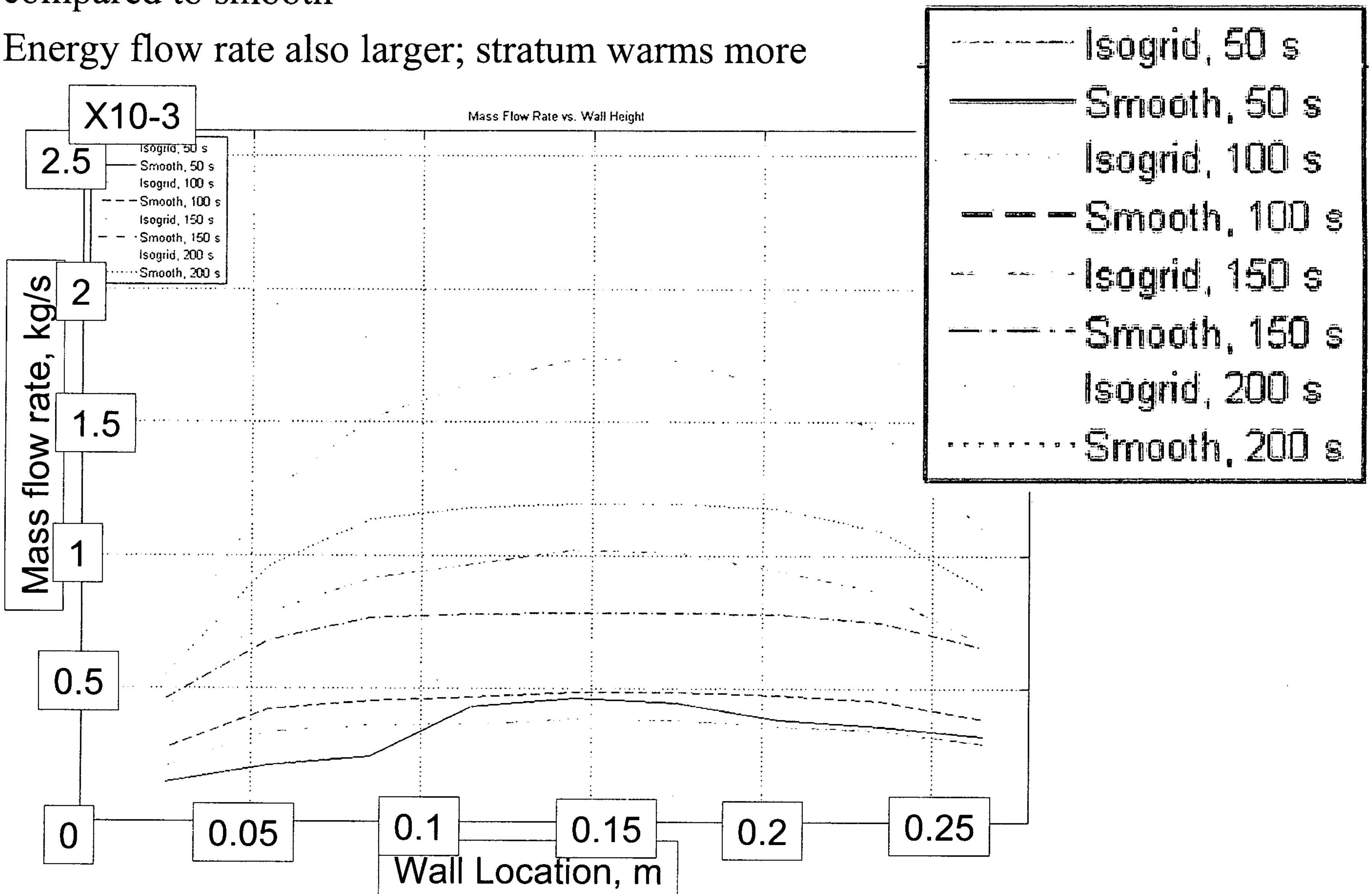
Computational Modeling : Rough walls

- Various cases run featuring different heat loads and gravity levels
- Sample case shown (geometry 1), $g/g_o = 10^{-2}$, $\theta = 5$ K, Water
- Rough wall tank compared to equivalent smooth wall case for constant wall temperature
  - Isogrid has larger thermal boundary layer,
  - larger boundary layer thickness,
  - u_{max} dependant on Gr (inc. relative to smooth with inc. Gr)



Computational Modeling : Rough walls

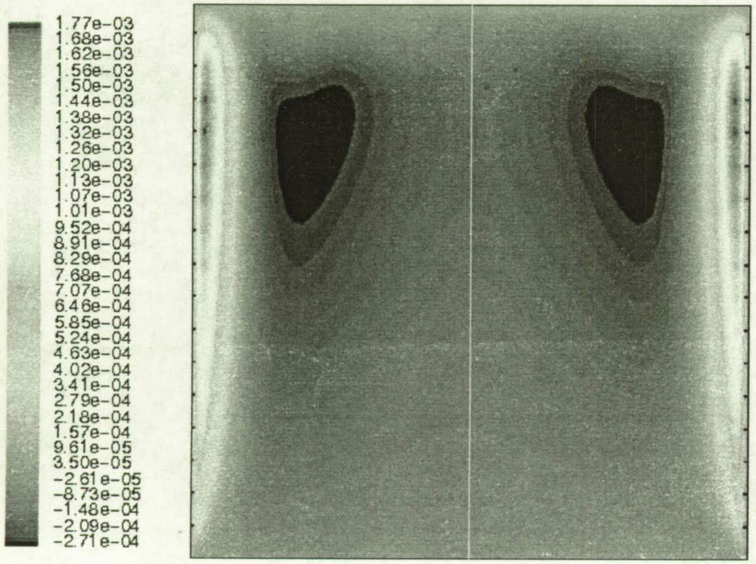
- At low gravity levels, Isogrid mass flow rate larger; fluid entrained faster compared to smooth
- Energy flow rate also larger; stratum warms more



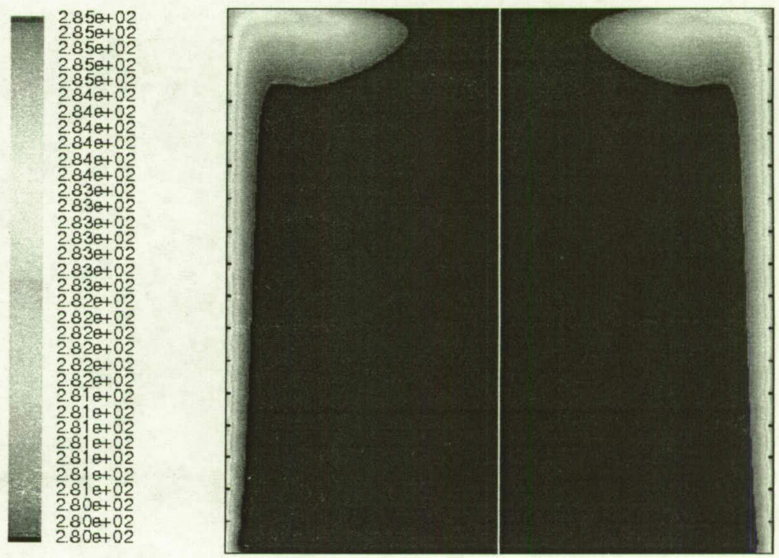
CONCLUSIONS

- Shown for low gravity levels that Isogrid boundary layers entrain fluid faster compared to smooth wall cases
- Results in an increase in stratification rate (up to 100% increase for certain geometries and spacecraft acceleration levels)
- Larger thermal boundary layers and increased heating area from Isogrid results in warmer stratum temperatures compared to smooth
- In addition, wall conduction is currently being added to models

Y-Velocity Contours



Temperature Contours



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